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COASTAL GEOMORPHOLOGY AND SAND BUDGETS APPLIED TO BEACH NOURISHMENT

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ABSTRACT

It is commonly assumed beach nourishment projects are more successful if applied over long distances of shoreline. Short projects tend to unravel at the ends as the bulge formed by the fill spreads alongshore. While these findings are relevant to many ocean beaches, particularly the east coast of Florida, numerous sites requiring nourishment are situated along pocket beaches, "drumstick" barrier islands, or coastlines subject to varying wave energy. Successful nourishment at such sites depends less on length than placement that takes advantage of local coastal processes and regional geomorphology. Constructed projects in South Carolina, a mesotidal coast with a variety of barrier beaches influenced by large tidal inlets, illustrate examples where local geomorphology, coastal processes, and sand budgets have been incorporated into the design in an attempt to improve longevity of the fill and use natural processes to advantage.

Case studies from Debidue Beach, Hilton Head Island, Fripp Island, and other sites included conceptual models of coastal processes and sand transport pathways. The qualitative models provide a regional view of the interaction of inlet and beach processes, the effects of offshore shoals on the distribution of wave energy, and natural morphologic indicators of net sand transport. Quantitative erosion surveys and sand budgets are used to test the validity of the conceptual models. This regional perspective makes it easier to formulate beach restoration plans for a particular site that occurs within the setting. Geomorphic models prepared early in the design process help define the surveys and data collection needs for a proper site analysis. They also provide a means of relating coastal processes and causes of erosion from one site to another despite the fact that most beach erosion problems are regarded as site-specific.

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causes of erosion from one site to another despite the fact that most beach erosion problems are regarded as site-specific.

INTRODUCTION

Beach nourishment is generally more successful if applied over long distances of shoreline. Short projects tend to unravel at the ends as the bulge formed by the fill spreads alongshore. While these findings are relevant to many ocean beaches, particularly the east coast of Florida, numerous sites requiring nourishment are situated along pocket beaches, "drumstick" barrier islands, or coastlines subject to widely varying wave energy. Successful nourishment at such sites depends less on length than on placement that takes advantage of site-specific coastal processes and regional geomorphology. Constructed projects in South Carolina illustrate examples where local geomorphology, coastal processes, and sand budgets have been incorporated into the design in an attempt to improve longevity of the fill and use natural processes to advantage.

GEOMORPHIC VARIATION OF BEACHES

Pioneering studies by Johnson (1919), Inman and Nordstrom (1971), Davies (1973), Hayes (1979) and others have provided broad classification schemes for shorelines. These classifications consider the role of plate tectonics (collision coasts versus trailing edge coasts), sediment texture (rocky to sandy to muddy), diagenesis (clastic or biogenic), and the hydrographic regime (microtidal to macrotidal; low to high wave energy). Considering clastic beaches, planforms and orientation vary primarily as a function of tide range, wave energy, and the occurrence of tidal inlets or structural headlands (Hayes, 1979).

When evaluating beach erosion trends and the feasibility of nourishment at a site, it is useful to place the locality in its regional context, consider where it fits in one of the classification schemes, and determine the primary controlling processes. Geomorphic indicators, such as spit growth, cuspate forelands, accretion fillets at groins, backshore vegetation, and profile geometry can be used to infer principal sand transport directions and whether a perceived erosion problem is long-term and regional, or short-term and localized.

TRADITIONAL NOURISHMENT APPROACHES

The traditional approach to beach nourishment has focussed on solving local problems as they arise. Normally, such efforts are initiated when one or more developed properties become imminently threatened by erosion. The site is surveyed and all historical shoreline data assembled to determine an erosion rate. The rate is used as a basis for determining fill quantities and estimated longevity of nourishment.

Long-term volumetric erosion data exist for relatively few localities in the United States; as a result, a nourishment requirement must often be derived from an extrapolated linear erosion rate. If the relationship between dune or mean high water recession and unit-volume erosion rate can be determined, a reasonable nourishment estimate is possible. However, at many sites, profile geometry, or the erosion rate, varies cyclically between periods of erosion and accretion, making estimates of volumetric nourishment requirements uncertain. Sediment variations along the profile also introduce uncertainties regarding the required nourishment quantity of a particular borrow sediment.

To overcome some of these uncertainties, nourishment projects are often formulated to extend beyond the problem area and account for the tendency for beach fills to unravel at the ends. Extra nourishment quantities beyond the minimum design quantity are sometimes placed in anticipation of postnourishment erosion rates being higher than historic rates.

While the traditional approach to nourishment planning has merit and is well established in practice, it can often be improved by consideration of the geomorphic variation of shorelines. Most projects can be made more efficient or cost-effective by incorporating natural sand transport pathways into the design, and considering alternating cycles of erosion and accretion in the renourishment schedule. Further, regular postproject monitoring is critical for evaluating the effectiveness of traditionally engineered as well as innovative nourishment schemes.

A number of beach restoration projects in South Carolina during the past decade illustrate how qualitative geomorphic models of shoreline evolution were integrated into the design process to attempt more efficient nourishment schemes. The sites described herein vary from traditional, long, uninterrupted barrier beaches by their higher tide range and moderate-to-low wave energy. Tidal inlets strongly influence the morphology and sand transport pathways along South Carolina beaches and other sites where tidal energy is high relative to wave energy.

BARRIER ISLAND MORPHOLOGY

Hayes (1979) classified barrier island morphology as a function of tidal and wave energy. The classic barrier island is a long, narrow island with a single, large dune ridge bounded at the ends by tidal inlets. The typical elongated planform of barrier islands becomes shorter and stubbier as tide range increases or wave energy decreases. Hayes demonstrated how many coastal barriers in mesotidal settings (generally a tide range of 2-4 meters) take on a "drumstick" shape (Fig. 1) and have multiple dune ridges. A key to this morphology is the influence of ebb-tidal deltas, features which tend to be more prominent where wave energy is low relative to tidal energy. Ebb-tidal deltas deflect shore-parallel contours and cause wave refraction and sheltering along adjacent beaches. The net result is a tendency for inlet-directed, net sediment transport along the beach in the lee of the delta. Where a predominant wave approach is oblique to the shoreline, the updrift end of the barrier is offset seaward of the adjacent beach because of sand accumulation in the shadow of the delta. A common feature along the oceanfront is a bulge similar to a cuspate foreland, where the downdrift edge of the delta intersects the beach. The location of the bulge shifts farther from the inlet as delta size increases. The combination of wave refraction, sheltering, and sand trapping at the updrift end of a mesotidal barrier produces a characteristic bulbous shape.

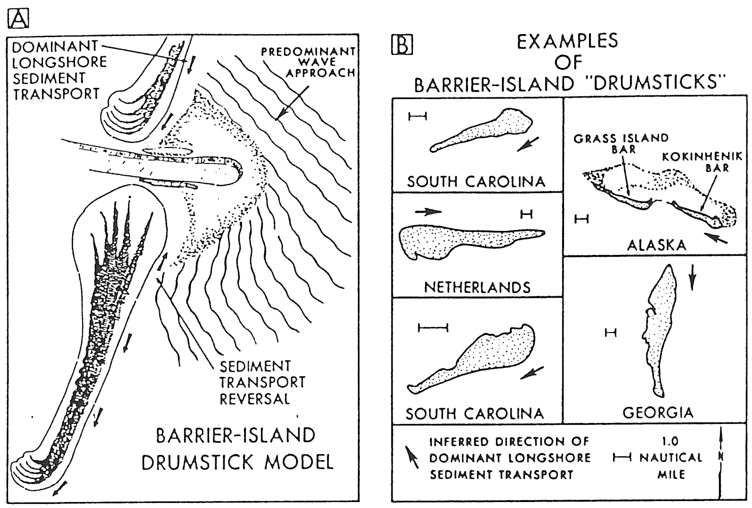


FIGURE 1. The barrier island drumstick model of Hayes (1979). Accumulation of sand at the updrift end often occurs episodically, producing localized zones and periods of accretion and erosion (from Hayes, 1979).

Away from the influence of the ebb-tidal delta, the principal transport direction and magnitude are controlled by the predominant waves. Natural evidence of a net sand transport along barrier beaches includes development of recurved spits, successive rows of curvilinear foredunes at the downdrift end of the island, and elongation of attached intertidal shoals in the downdrift direction.

As inlet size increases, the ebb-tidal delta may directly affect wave energy distribution over the entire length of the barrier beach. This gives rise to more random planforms at the shoreline and deviations from the classic drumstick shape. Barrier islands of Georgia and southern South Carolina tend to have multiple cuspate features along the ocean shoreline. Bulges may occur anywhere along the beach in association with offshore topography and resulting variations in wave energy.

COASTAL MORPHOLOGY AND BEACH NOURISHMENT PLANNING

It is useful to consider the regional morphology and shoreline classification schemes before developing plans for nourishment. This provides the context for an erosion assessment and a conceptual model of sand transport pathways along a beach. The planning approach we have taken in over 50 shoreline assessments and a dozen nourishment projects in the last decade is outlined in Figure 2. While this is a common study approach for shoreline erosion problems, it differs in one respect. It includes preparation of a conceptual erosion/coastal processes/sand transport model based on a regional site evaluation. In a number of cases, the conceptual model was theorized using comparisons from similar settings and the quantitative analysis and data collection designed around the model. Following are several case examples from South Carolina which illustrate application of this approach.

Debidue Beach

Debidue Beach is a six-mile-long barrier spit in north central South Carolina. A residential development exists along two miles of the center of the barrier. This area has experienced erosion, and a vertical bulkhead was installed along the south half of the development around 1980. Historical data show the length of developed beach has been stable at the north end but increasingly erosional to the south (Kana et al., 1985a) (Fig. 3). A sequence of historical, vertical aerial photographs confirm the erosion trend and rate have been relatively steady since 1950.

Review of the regional geomorphic setting suggests why the site-specific erosion rates given in Figure 3 persist. The northern end of Debidue Beach terminates at Pawleys Inlet, an unstable, migrating channel with a small tidal prism [order 10^6 cubic meters (m^3)]. The inlet's ebb-tidal delta extends approximately one quarter mile offshore, making it one of the smallest along the South Carolina coast. Sand bypassing occurs in conjunction with southerly inlet migration and periodic breaching of the updrift

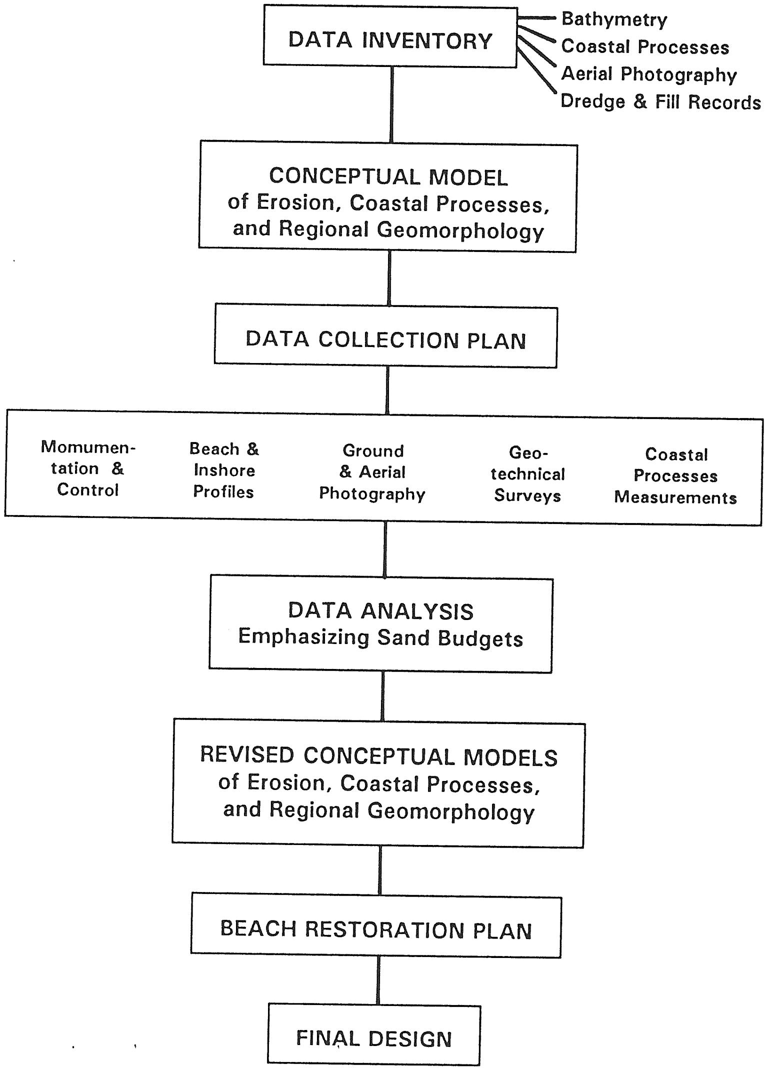


FIGURE 2. Planning approach to beach nourishment projects incorporating conceptual models of coastal processes and regional geomorphology.

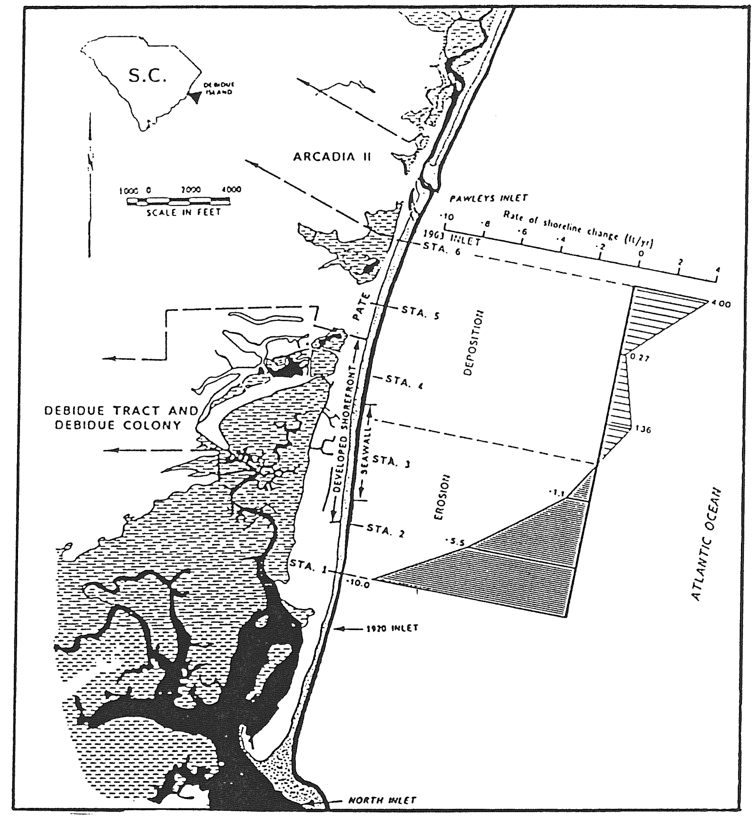


FIGURE 3. Erosion trends along Debidue Beach between 1950 and 1980. Oceanfront development is presently limited to the reach between stations 1 and 4 (from Kana et al., 1985).

spit, adding to the sediment supply along northern Debidue's oceanfront. During the past 40 years, the supply of sand to the northern one-third of Debidue Beach has exceeded the rate of southerly transport, producing the zone of accretion shown in Figure 3 (stations 4, 5, and 6). In contrast, the supply of sand to the center of the island has not kept pace with the longshore transport rate. This has resulted in a trend of increasing erosion to the south (Fig. 3, stations 1, 2, and 3). A possible explanation for the increasing erosion rate would be an increasing longshore component of wave energy flux to the south. However, there is no obvious change in offshore topography or shoreline orientation to produce such an increase. On closer inspection, the higher erosion rate toward the south appears linked to the history of North Inlet, the inlet to the south.

North Inlet has a tidal prism averaging 1.5 x 10^7 m^3, over an order of magnitude greater than Pawleys Inlet (Finley, 1976). In the 1920's, a channel of the inlet crossed Debidue spit about one-half mile south of station 1 (Fig. 3). The seaward terminus of the delta may have extended upwards of three-quarters of a mile offshore, similar to today's inlet. Since the 1920's, Debidue spit has accreted rapidly, filling the channel south of station 1 and consolidating its flow in the present channel about one and a half miles south of station 1. As the inlet shifted south, trailing shoals left a bulge in the shoreline where the 1920's channel had been. Further, the azimuth of the spit shifted slightly west from the strandline of the rest of the island. This change in azimuth is probably due to overwash of the newly accreted spit, creating a deficit in the littoral budget. Updrift of the 1920's inlet, a series of forested beach ridges reduced sand losses to washovers and preserved the littoral budget seaward of the foredune. But a broad lagoon landward of the accreting spit provided room for washover sand to accumulate. Washovers robbed sand from the littoral budget and probably produced the change in azimuth of the shoreline compared to the updrift end of Debidue Beach.

Jumping ahead to the early 1970's when the first residential development occurred along Debidue, the overall shoreline morphology was set. North Inlet had stabilized in its present position about one and a half miles south of station 1. Its ebb-tidal delta functioned as the primary downdrift boundary for the Debidue Island littoral compartment. Pawleys Inlet formed the northern littoral boundary. Normally, a shoreline in equilibrium between two tidal deltas would be slightly arcuate in planform. But Debidue, during this period, differed by the persistence of the remnant bulge where the 1920 inlet had been. Since the 1970's, the bulge has eroded rapidly due to its exposure and the natural tendency of an arcuate shoreline to develop between the present inlets. Two timber sheetpile groins were installed in the early 1970's in recognition of erosion at this point. However, by the mid 1980's, both had deteriorated beyond repair and no longer functioned to trap sand. The bulge has eroded at an average of more than 12 ft per year for the period 1950-1985. With development situated only 0.5-2.0 miles updrift, erosion has become the dominant trend for central Debidue Beach, but the rate diminishes toward Pawleys Island. Figure 4 is a conceptual geomorphic model which illustrates the net result of these inlet-associated processes.

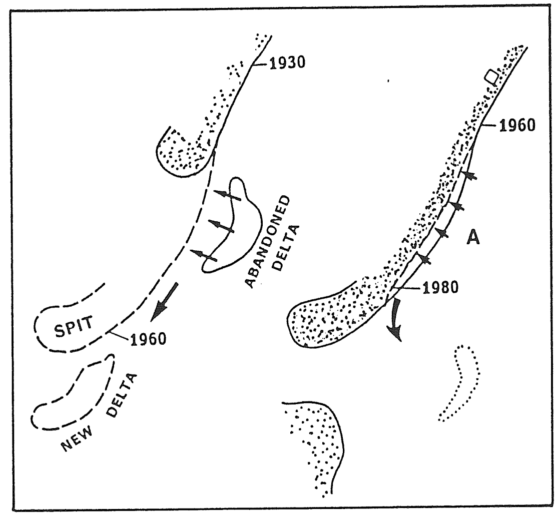


FIGURE 4. Conceptual model of erosion for Debidue Beach. The bulge at A is a remnant feature from trailing shoals left as the unstable downdrift inlet migrates south.

Restoration Plan. CSE formulated a beach restoration plan for the developed section of Debidue Beach based on the regional morphologic trends and a sand budget extrapolated from linear erosion rates and profile geometry (CSE, 1989). Beach nourishment at varying rates according to profile deficits and the site-specific erosion rate was implemented in spring 1990 [total 180,000 cy (±21.4 cy/ft) from an inland source by trucks]. A second part of the plan calls for construction of a terminal groin or breakwater near station 1 to anchor the downdrift end of the beach. While the downdrift shoreline, which is a nature preserve, would be incrementally impacted by construction of a terminal structure near station 1, the greater impact to the area stems from persistent erosion of the bulge and chronic sand losses to washovers. Healthy dunes between the bulge and North Inlet were lost during the period 1975 to 1985. Hurricane *Hugo* in September 1989 proved the vulnerability of the southern spit by overwashing the entire feature and producing a temporary breach channel at the site of the 1920 inlet. Without a downdrift trap for beach nourishment along the development, maintenance fill will be required at increasing rates because of the geomorphic changes from the bulge to North Inlet. With a properly designed groin near station 1, renourishment rates along the development would be reduced.

Hilton Head Island

Hilton Head Island is a 12-mile-long, barrier island near the South Carolina-Georgia border. In contrast to Debidue Beach, it is bounded by much larger tidal inlets, Port Royal Sound at the north end and Calibogue Sound at the south. Tidal prism for Port Royal Sound is of the order 10^9 m^3, or about three orders of magnitude greater than Pawleys Inlet. The seaward terminus of its ebb-tidal delta extends over five miles offshore. The southern edge of the delta terminates at Gaskin Banks, a series of shoals about 1.5 miles offshore. The shoals of Port Royal Sound control wave energy distribution and the morphologic development of Hilton Head, forming a bulbous updrift end and a recurved spit at the south end. But as a variation on the classic drumstick shape of many mesotidal barriers (Hayes, 1979), the updrift bulge associated with the terminus of Port Royal Sound's ebb-tidal delta is situated near the mid point of the island in the lee of Gaskin Banks. This gives the shoreline the planform of the sole of a boot (Fig. 5).

A 1986 erosion assessment (Kana et al., 1986) documented volumetric erosion rates and sand budgets for the island. The results confirmed a ±20 year trend of retreat of the shore along the center of the beach and accretion at the ends; less quantitative data for longer periods confirmed a similar trend. In contrast to Debidue Beach, little sand exchange occurred between the shoals of the ebb deltas and the beach during the recent 20-year period because of the separation distance. The principal influence of the inlets is their effect on the distribution of wave energy along the shoreline.

Using sand budget data and geomorphic evidence, CSE prepared a conceptual model of coastal processes affecting Hilton Head Island. In follow-up studies (Phase II), Olsen Associates performed wave-refraction tests (Olsen Associates, 1987) and designed a ±2.5 million cy nourishment project that was implemented in summer 1990. Nourishment design analysis supported the earlier conceptual model of erosion and sand transport pathways. The finished project targeted the critical central 35,000 ft of shoreline between Forest Beach and the area just north of The Folly (Fig. 5) and assumed losses will include migration of fill to each end of the island. Postproject surveys by Sea Island Engineering and Olsen Associates in 1991 appear to confirm these site-specific transport patterns.

Fripp Island

Fripp Island is a three-mile-long, mesotidal barrier along the southern South Carolina coast. It is bounded at the north by Fripp Inlet, a moderately large, natural inlet with a tidal prism of the order 10^8 m^3 and an ebb-

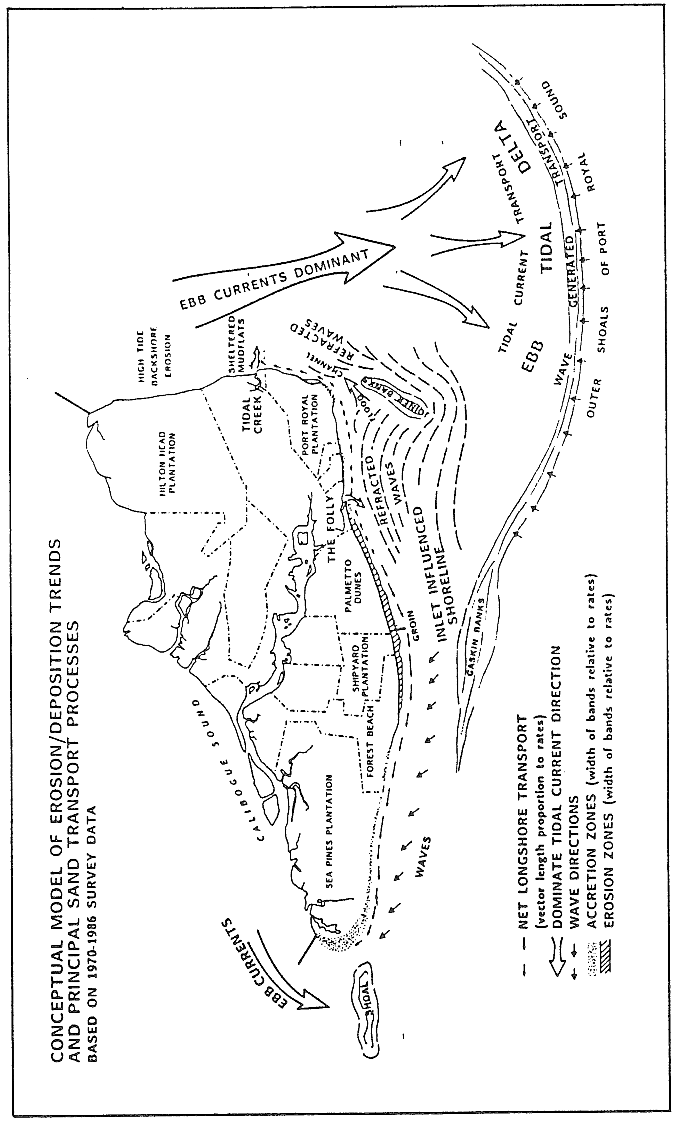


FIGURE 5. Conceptual model of erosion processes, sand transport pathways, and erosion/deposition trends affecting Hilton Head Island, South Carolina, inferred from 1970-1986 survey data, geomorphology, and comparison with similar barrier-island settings (from Kana et al., 1986).

tidal delta that terminates about one mile offshore. Skull Inlet, a small tidal channel carrying a prism of the order 10^6 m^3, forms the southern boundary. Similar to Hilton Head Island, the updrift inlet dominates the setting, producing a major sand trap for littoral transport from the adjacent beaches. In fact, the size of the ebb-tidal delta in relation to the length of Fripp Island alters wave energy along most of the beach. Refraction around the Fripp Inlet shoals and the sheltering effect of the tidal delta produce net sand transport to the north along most of the island.

During the past 20 years, an attached shoal (New Haven shoal on Fig. 6) has grown several times in area and presently forms a triangular-shaped, attached shoal extending along the northern one third of the beach. In the mid 1970's, New Haven shoal extended only 2,000 ft south of the inlet (CSE, 1990). This pattern of sand trapping by Fripp Inlet has accentuated refraction of waves into the shoreline. Regardless of deep-water incidence, waves tend to break obliquely along Fripp and drive most sand north toward the inlet. Transport only reverses at the south end, about 0.5 to 1.0 mile from Skull Inlet. The net result is rapid loss of sand along the center of the island and accretion at the north end. The south end has been moderately accretional along the oceanfront but unstable at the Skull Inlet margin because of deflection of the channel by the Pritchards Island shoal (Fig. 6). Shore-protection measures to date have emphasized construction of revetments and several groins at the south end (Bruun, 1975).

Sand budgets for Fripp Island, covering the past decade, suggest the erosion trend along the center of the island will persist as long as the Fripp Inlet and New Haven shoals exist. CSE (1990) estimates the ten-year sand deficit is of the order 1.0 to 1.5 million cubic yards. This quantity could be added gradually over a multiyear period to restore a ± 50 ft, dry-sand beach and keep pace with the erosion rates of the 1980's. However, a project formulated as such will remain subject to the same set of processes that are causing the problem. An alternative approach proposed would involve excavation of at least 2.0-2.5 million cubic yards from New Haven shoal and other portions of the Fripp Inlet delta (Fig. 7). This would obviously provide a wider beach with greater longevity, but more importantly, it would reduce the size of the delta and its effect on wave refraction. Removal of this quantity could be performed while leaving a sizeable shoal extending over 1,000 ft offshore. A carefully planned excavation could provide a sink for more seaward shoals to infill. This would have the effect of moving the terminal lobe of the delta closer to shore and lessening the effect of the delta on wave refraction. Such a scheme should also be combined with nourishment and dune enhancement in the lee of New Haven shoal to improve protection to properties in reach 1 (Fig. 6). As of this writing, the community has voted against proceeding with any major beach restoration work.

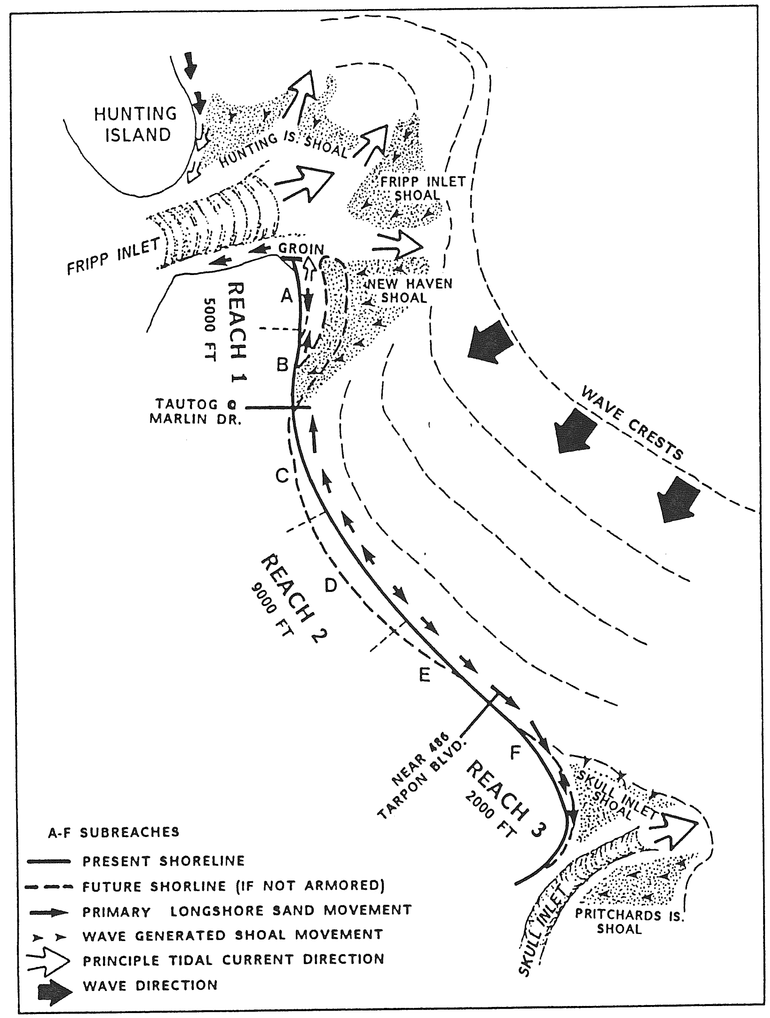


FIGURE 6. Conceptual model of erosion and coastal processes affecting Fripp Island's (South Carolina) shoreline in 1989. Reach 1 is in the lee of New Haven shoal and is gaining sand. Reach 2 is the central armored area of the island that lacks a high-tide beach. Reach 3 is the south spit that has been stable to slightly accretional. Boundaries between the reaches are approximate. [From CSE, 1990]

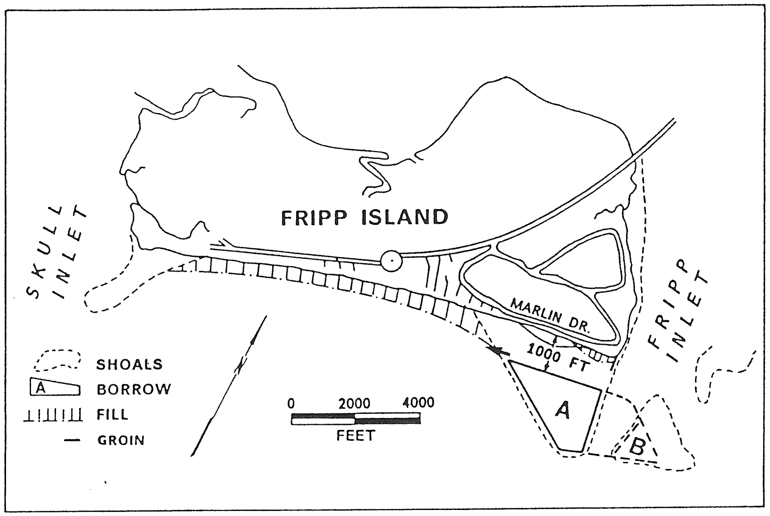
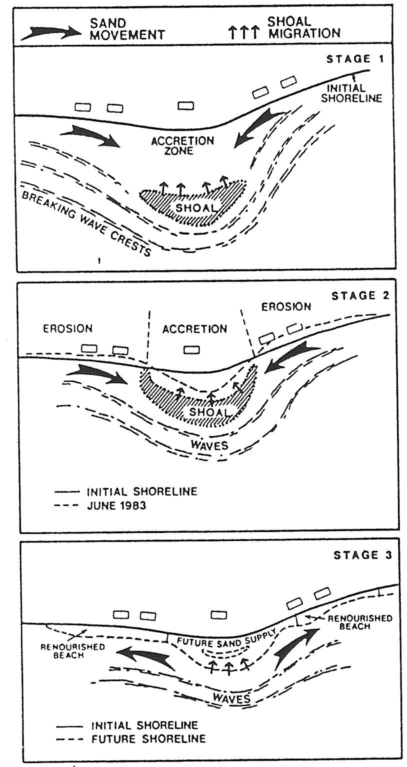


FIGURE 7. Proposed nourishment plan for Fripp Island involving major excavation of the ebb-tidal delta to reduce the degree of wave refraction and northerly transport toward Fripp Inlet (from CSE, 1990).

OTHER APPLICATIONS

Conceptual models of coastal processes and shoreline morphology have been prepared for over a dozen South Carolina sites and have been incorporated into the design of beach restoration projects. A small-scale problem developed at the north end of Isle of Palms in 1982 whereby a 0.5 million cubic yard shoal detached from the adjacent inlet and migrated ashore. This shoal bypass produced rapid accretion in its lee, but severe erosion along the adjacent beaches (Fig. 8). As documented in Kana et al. (1985a) and Williams et al. (1987), the area was eventually restored by selective nourishment along the eroding arcs and natural spreading of the attached shoal. Other examples include restoration of a portion of Seabrook Island by inlet relocation (Kana, 1989) and the fifth nourishment project at Hunting Island in 1991 (CSE, 1991). While some of these projects are too recent to evaluate, they have benefitted from the application of conceptual geomorphic models.

FIGURE 8. Model for shoreline changes at Isle of Palms between 1982 and 1986. Shoal bypasses in 1983 and 1985 added to the sand budget of the island, but also caused short-term erosion problems adjacent to the points of attachment (from Williams and Kana, 1987).



SUMMARY

When combined with traditional analytical techniques in nourishment design, conceptual models of coastal processes and morphologic trends offer an easily understandable framework for defining beach erosion problems. They can be used to test theories regarding causes of erosion, to guide the selection of survey sites and analytical techniques, and to explain to laymen the basic nature of coastal processes at a site. The examples of beach restoration schemes for Debidue Beach, Hilton Head Island, and Fripp Island illustrate the highly variable nature of erosion along mesotidal barriers. Morphologic models can simplify the design process but certainly do not guarantee success. But with such models, implemented projects can be monitored to test their general validity. It is commonly acknowledged that erosion problems are site-specific. A coastal process/morphologic model can help identify similarities with other sites and reduce some of the uncertainty in design of nourishment.

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